Hidden Photon Dark Matter Search with a Large Metallic Mirror

Babette Döbrich[1], *Kai Daumiller*[2], *Ralph Engel*[2], *Marek Kowalski*[1,3], *Axel Lindner*[1], *Javier Redondo*[4], *Markus Roth*[2]

[1]Deutsches Elektronen-Synchrotron (DESY), 22607 Hamburg and 15738 Zeuthen, Germany
[2]Karlsruher Institut für Technologie (KIT), IKP, 76021 Karlsruhe, Germany
[2]Humboldt Universität, Institut für Physik, 12489 Berlin, Germany
[4]Zaragoza University, Pedro Cerbuna 12, E-50009 Zaragoza, Spain

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-03/doebrich_babette

If Dark Matter is composed of hidden-sector photons that kinetically mix with photons of the visible sector, then Dark Matter has a tiny oscillating electric field component. Its presence would lead to a small amount of visible radiation being emitted from a conducting surface, with the photon frequency given approximately by the mass of the hidden photon. Here, we report on experimental efforts that have started recently to search for such hidden photon Dark Matter in the (sub-)eV regime with a prototype mirror for the Auger fluorescence detector at the Karlsruhe Institute for Technology.

1 Ultralight Dark Matter and the dish principle

In the literature there is no shortage of well-motivated candidates for cold Dark Matter (DM) particles. Without going into details of their respective theoretical motivation, it is however clear that there is more experimental work needed in the search for its ultra-light candidates below the eV regime: Although different detection schemes have been proposed, only a few laboratory Dark Matter searches are actively searching for low-mass particles such as QCD Axions, see, e.g., recent progress of the Axion Dark Matter eXperiment (ADMX) [1] and EDM-based techniques [2].

Considerations of general classes of ultra-light particles, dubbed 'weakly interacting slim particles' (WISPs) [3] have shown that such particles could make up the Dark Matter in a rather large parameter space: particularly axion-like particles (ALPs) and massive hidden photons (HPs) [4] can in principle constitute all of the cold Dark Matter mainly through the misalignment mechanism which is also invoked for Axions, see [5]. Whilst the viable parameter space for such ultra-light Dark Matter is likely to be further constrained from cosmological observables, ultimately laboratory experiments should be performed to have certainty on its existence.

On the experimental side, set-ups like ADMX are based on a *resonant* conversion of axions (and WISPs) and are thus ideal to find extremely weakly coupled particles in a rather narrow mass region. This is ideal for a QCD axion Dark Matter search. For covering a wider mass-range, the search for ALP and HP Dark Matter with a spherical mirror has been recently proposed [6]: Here the conversion is *not resonantly amplified* and thus the most immediate experimental setups are less sensitive with respect to the coupling (but have the advantage of broad-band frequency/mass coverage).

Let us recapitulate the idea of the 'dish setup' for HP Dark Matter, analogous considerations hold then for ALPs[1]: The relevant term for HP DM $\tilde{\gamma}$ is photon-to-hidden-photon coupling, parameterized by the kinetic mixing parameter χ, see, e.g. [4]. It eventually leads to electromagnetic power being emitted by a conducting surface (e.g. mirror) at angular frequencies approximately corresponding to the HP mass, $\omega \simeq m_{\tilde{\gamma}}$ [6]. This is due to the presence of the HP DM together with the usual requirement that for electric fields at the conducting surface $\vec{E}|_{\parallel} = 0$. To first order, photons are emitted perpendicular to the surface, with small corrections stemming from directionality of the DM inflow (which can be used to verify its DM origin).

To detect photons induced by this process, the advantage of using a spherical mirror is imminent: photons from far away background sources impinging on the mirror will be focused in the focal point $f = R/2$ whilst the Dark-Matter-induced photons will propagate to the center of the 'mirror sphere'. There, a detector can be mounted. A small off-set away from the center can be understood as follows: Be $\vec{p}$ the momentum of the incoming DM, and $\vec{k}$ the outgoing photon momentum, then $k_{\parallel} = p_{\parallel}$ along an infinitely extended surface because there is no boundary change (the approximation is then valid as long as λ is much smaller then the surface diameter). With energy conservation $\vec{k} = \sqrt{m^2 + |\vec{p}_{\perp}|^2}\vec{n} + \vec{p}_{\parallel}$, with normal $\vec{n}$ to the surface. As for the DM $|\vec{p}| \ll m$, the angular off-set of the signal away from the center of the 'dish-sphere' is $\psi \simeq |\vec{p}_{\parallel}|/m$ and the off-set on the detector is $d_i \simeq \frac{p_i}{m}R$ when the detector is at center R and i labels directions along the surface.

Nicely, thus, such a setup has a directional sensitivity [7], which is easy to retrace within the common DM halo models. E.g., assuming an isotropic velocity distribution of the DM with respect to the galactic frame, a global off-set of the signal on the order of $\Delta d \sim \Delta v_{\mathrm{detector}} R$ is expected due to the movement of the sun in the galactic rest frame as well as a daily modulation on the same order of magnitude (the yearly modulation is negligible due to the small velocity of the earth w.r.t. the sun). Besides the signal-spot movement, a likely velocity distribution $\Delta v_{\mathrm{DM}} \sim 10^{-3}$ of the DM leads to a broadening of the signal spot. Ultimately, it is nice that this directional sensitivity can help to verify the Dark Matter nature of a signal.

2 Prospective sensitivity with the KIT mirror

The Pierre Auger Observatory uses two types of mirrors (coated glass and coated aluminum) [8]. Both are are segmented due to their rather large overall area of $A \simeq 13\mathrm{m}^2$, see Fig. 2. One prototype aluminum mirror for this experiment is kept at the Karlsruhe Institute for Technology (KIT). As the mirrors are spherical with $R = 3.4$m, the metallic mirror is ideal for the Dark Matter search described above. Assuming a Dark Matter density of $\rho_{\mathrm{CDM}} \simeq 0.3\mathrm{GeV/cm}^3$ and assuming that HPs make up all of the Dark Matter the power emitted to the center is

$$P = \langle \alpha^2 \rangle \, \chi^2 \rho_{\mathrm{CDM}} A_{\mathrm{dish}} \approx \chi^2 \; (1.87 \times 10^5 \text{ Watt}) \; , \tag{1}$$

where $\langle \alpha^2 \rangle$ is a $\mathcal{O}(1)$-factor related to the polarization of the HPs [6], which we have taken to be one for simplicity. As mentioned, the experimental advantage now is that the power is concentrated at the center R of the 'mirror sphere', and not at the focal point $f = R/2$.

[1]From the experimental point of view, to look for ALP DM with this technique is rather involved, since for a decent sensitivity the mirror has to be strongly magnetized with field strengths on the order of a few Tesla [6]. For the experimental setup at KIT described here, this will likely not be possible.

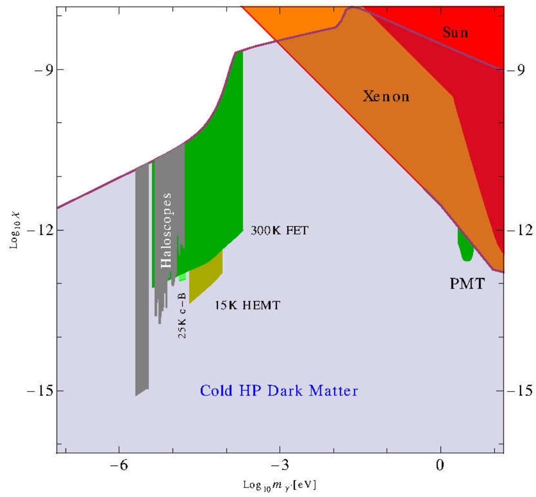

Figure 1: Hidden photon DM parameter space (blue) and exclusion regions (red/orange). In green some parameter regions accessible with the metallic mirror setup with different detector options. See text for details and [4] for a comprehensive review of the parameter space.

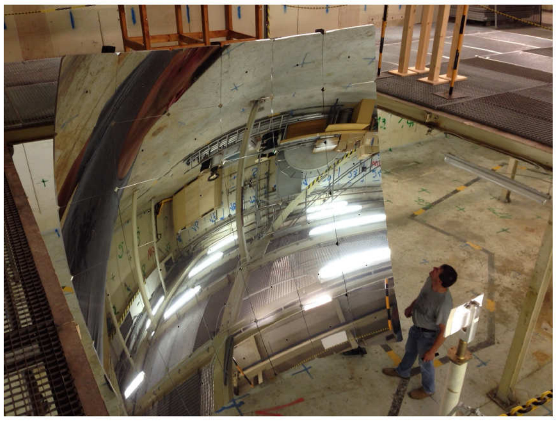

Figure 2: Spherical prototype mirror for AUGER housed at KIT (campus north). The grey post at the lower right hand side is the detector mount located in the center of curvature.

As benchmark number, one would like to probe the parameter space below $\chi = 3 \times 10^{-12}\ 1/m[\text{eV}]$, which is the limit inferred from the XENON10 experiment [9], see the orange region labeled 'Xenon' in Fig. 1.

The setup described above is sensitive to all HP masses whose associated wavelength $\lambda = 2\pi/m$ can be: 1) detected by the sensor and 2) properly focused by the mirror (here we assumed $\lambda \ll R$ to use light-ray approximation and neglect diffraction, which would affect our estimates approximately below the mass range at which we cut Fig. 1).

For technological simplicity, measurements in the visible are a good starting point, although their range is a limited. As an example, labeled 'PMT' in Fig. 1, we have plotted the sensitivity range of a readily available[2], low-noise ($\lesssim$1Hz) cooled PMT with $\sim$ 25% quantum efficiency in the (300-500)nm regime at a SNR of 3 and 30h measurement time (assuming we are noise-limited by the detector, which is conceivable in the optical).

One can see that even this most simple and realistic setup is quickly sensitive to uncharted parameter space and with a set of PMTs, the near-infrared to UV range can be explored down to $\chi \sim 10^{-13}$ (the overall coverage is a bit limited in the eV-range due to the strong bounds imposed by [9]).

Since the mirror is by default set up in a room with $\mathcal{O}$(m)-thick concrete walls and further shielding can be constructed if required, measurements down to the GHz-range can be envisioned and are sensitive to larger parameter regions of HP DM. The gray regions in Fig. 1 indicate the exclusion set through a null-result of different QCD axion haloscopes as described in Sect 1.

[2] see, e.g. `http://my.et-enterprises.com/pdf/9893_350B.pdf`.

In green and yellow, again we plot parameter space accessible in principle to our set-up, here within a few minutes in an idealized situation where we are limited by detector noise (if the mirror has high reflectivity for the corresponding frequencies, its thermal emission should be low). We sketch the accessible parameter region using the Dicke radiometer equation for a 25K c receiver at hand ($\sim 3.2 - 4.2$GHz) (lighter green). For slightly higher frequencies we employ the noise figure provided in [10]. One sees that even non-cryogenic options (300K FET, darker green) can cover a neat section of parameter space, we also plot in lighter green the accessible region for a 15K HEMT (yellow).

Note the in the above considerations we have left out implications of directionality discussed in Sect 1. In the final analysis, the data sets have to be evaluated in a particular DM model in which off-set and modulation can be computed.

In summary, one sees that this rather simple setup offers many options to look for HP Dark Matter. Fig. 1 just sketches the most immediate options for this setting for good experimental conditions. If we are successful in these first steps, measurements in also in intermediate frequency ranges could be conceived. In the following months, the results of ongoing background measurements and budgetary considerations will determine our next steps.

3 Summary

Hidden Photons could constitute (part of) Dark Matter. To test this possibility, cosmological guidance and laboratory experiments are needed. A novel setup with a large metallic mirror that can probe HP masses in the $10^{-5} - 10^{0}$ eV-regime down to kinetic mixing values of $\chi \sim 10^{-13}$ is being set up at Karlsruhe. This experiment can nicely complement other broadband efforts [11] to probe even lower HP DM mass-scales with microwave cavities.

The authors acknowledge the support of the Helmholtz Alliance for Astroparticle Physics, the lasting support of many 'light-movers' [12] and the kind collaboration of I. G. Irastorza, J. Jaeckel, D. Horns, H. Krüger, A. Lobanov, H.-J. Mathes, A. Ringwald, J.-E. v. Seggern, G. Woerner and D. Veberic on different aspects of this experiment. BD would like to thank the PATRAS 2014 workshop organizers for a topical and motivating conference.

References

[1] I. P. Stern, AIP Conf. Proc. **1604**, 456 (2014) [arXiv:1403.5332 [physics.ins-det]].

[2] D. Budker *et al.*, Phys. Rev. X **4**, 021030 (2014) [arXiv:1306.6089 [hep-ph]].

[3] K. Baker *et al.*, Annalen Phys. **525**, A93 (2013) [arXiv:1306.2841 [hep-ph]].

[4] J. Jaeckel, Frascati Phys. Ser. **56**, 172 (2012) [arXiv:1303.1821 [hep-ph]].

[5] P. Arias *et al.*, JCAP **1206**, 013 (2012) [arXiv:1201.5902 [hep-ph]].

[6] D. Horns *et al*, JCAP **1304**, 016 (2013) [arXiv:1212.2970].

[7] J. Jaeckel and J. Redondo, JCAP **1311**, 016 (2013) [arXiv:1307.7181].

[8] J. Abraham *et al.* [Pierre Auger Collaboration], Nucl. Instrum. Meth. A **620**, 227 (2010).

[9] H. An, M. Pospelov and J. Pradler, Phys. Rev. Lett. **111**, 041302 (2013) [arXiv:1304.3461 [hep-ph]].

[10] S. Weinreib, W. Pospieszalski and W. Norrod, 1988 IEEE MTT-S Digest

[11] P. W. Graham, J. Mardon, S. Rajendran and Y. Zhao, arXiv:1407.4806 [hep-ph].

[12] J. Redondo and B. Döbrich, arXiv:1311.5341 [hep-ph].
`https://indico.desy.de/conferenceDisplay.py?confId=7975`